TRAC-M-TR-17-009
12 January 2017

Force 2025 and Beyond Strategic Force Design Analytic Model

U.S. Army TRADOC Analysis Center-Monterey
700 Dyer Road, Room 176
Monterey, California 93943-0692

TRAC-M-TR-17-009
12 January 2017

Force 2025 and Beyond Strategic Force Design Analytic Model

LTC Casey Connors
Dr. Paul L. Ewing Jr.

This study cost the
Department of Defense approximately
$244,000 expended by TRAC in
Fiscal Years 15-17.
Prepared on 20170106
TRAC Project Code # 020309

U.S. Army TRADOC Analysis Center-Monterey
700 Dyer Road, Room 176
Monterey, California 93943-0692

This page left intentionally blank.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
12-01-2017	Technical Memorandum	October 2015 – November 2016

4. TITLE AND SUBTITLE Force 2025 and Beyond Strategic Force Design Analytic Model	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) LTC Casey Connors	**5d. PROJECT NUMBER** 020309
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) TRADOC Research Analysis Center, Monterey, CA Naval Postgraduate School, Monterey, CA	**8. PERFORMING ORGANIZATION REPORT NUMBER** TRAC-M-TR-17-009
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) TRADOC Analysis Center, Headquarters, Fort Leavenworth, KS	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report documents the F2025B Force Design Analytic Model research conducted by TRAC-MTRY and the Naval Postgraduate School. Our research develops a methodology for conducting quick-turn force design analysis given a mission and constraints; it helps us to more fully understand the trade space between different force designs. We describe a data development methodology that characterizes the data required to construct a force design model using our approach. We formulate a mixed integer program optimization model and provide an implementation using GAMS and CPLEX. Finally, we analyze a resultant force design from a model constructed using this methodology in a case study.

15. SUBJECT TERMS
Force design, mixed integer programming, optimization, value focused thinking, functional hierarchy, task capability matching

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** LTC Casey Connors
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	U		**19b. TELEPHONE NUMBER** ***(include area code)*** (831) 656-7575

This page left intentionally blank.

Acknowledgements

We would like to acknowledge the contributions made to this project by Professor Lee Ewing, Professor Dave Alderson, Professor Imre Balogh, and Mr. Mike Bailey. We would also like to thank MAJ Cardy Moten for his R coding contributions.

This page intentionally left blank.

Table of Contents

This page left intentionally blank.

Introduction

Purpose

This report documents the F2025B Force Design Analytic Model research conducted by TRAC-MTRY and the Naval Postgraduate School. Our research develops a methodology for conducting quick-turn force design given a mission and constraints; it helps us to more fully understand the trade space between different force designs. We describe a data development methodology that characterizes the data required to construct a force design model using our approach. We formulate a mixed integer program optimization model and provide an implementation using GAMS and CPLEX. Finally, we analyze a resultant force design from a model constructed using this methodology in a case study.

This document is organized into two sections. In the Methodology section, we provide an overview of the methodology used to construct force design models. The Summary section provides a summary of our findings.

Background

By 2025, a leaner, smarter, more lethal, and flexible Army must operate differently, enable forces differently, and organize differently to maintain overmatch, capable of responding to a myriad of threats to our nation’s national interests, and to set the conditions for fundamental long-term change. To determine the optimal design for the Army of the future, the Force 2025 and beyond effort consists of activities along three primary lines of effort: force employment; science and technology and human performance optimization; and force design. F2025B seeks a structure enabled and optimally organized to conduct expeditionary operations and fully capable of Globally Integrated Operations while ensuring overmatch.

TRADOC, and by extension, TRADOC Analysis Center (TRAC), conducts analysis to support force design decisions, including operational effectiveness analysis. Given the environment that future forces will need to operate in, TRAC requires analytic capabilities to describe an enabled and optimally organized F2025B.

To that end, we seek to create a model that assists decision makers in exploring design options in the context of Army operations. The intent of this research is to describe and evaluate current organizational designs in terms of Force Employment and Force Design using the model to offer recommendations and analysis that could improve the effectiveness of the force as it transitions to F2025B. The end result is a force design model capable of providing insights into organization impacts of potential changes from the Wargaming and Experimentation Season.

From this central motivation, a methodology is developed to illuminate the current organizational design structure to better understand how the network of BCTs and enablers function in today’s steady state environment. This effort will enable a level analysis based on structural groups within the current organizations that possess a level of competence, capability and capacity to execute missions and provide support. The idea is to align units with inherent capabilities to tasks described by Army doctrine, then map those tasks to defined, scenario-driven missions. This follows the ends-ways-means approach to modeling a force for carrying out a specified operation.

One area of force design analysis that this research may particularly benefit are so-called enabler organizations. These organizations include logistics and protection units, among others, that provide services to main warfighting organizations, such as Divisions and BCTs, to allow decisive operations.

Project Problem Statement and Objectives

Research a methodology for developing a strategic level visualization tool for force design in order to more fully understand the Force 2025 and Beyond (F2025B) trade space. Our objectives are to:

1) Use Mixed Integer Program optimization to better understand and visualize the structural relationships and interactions of Force Employment and Force Design of the current structure of Army BCTs and enablers.
2) Develop a proof-of-concept Mixed Integer Program optimization model based on the ends-ways-means strategic construct that informs force design for F2025B from strategic to tactical fidelity given a set of strategic missions.
3) Demonstrate use of the model for quick turn force shaping analysis for enabler units in one enabler area: Air and Missile Defense; within one phase of Army operations: Phase II: Seize the Initiative.

Constraints, Limitations, and Assumptions

Constraints limit the project team's options to conduct the study. For this research, we identify the following constraints:

- Complete the project no later than March, 2017. We are able within these constraints to provide only an initial foray into this methodology.

Limitations are a project team's inabilities to investigate issues within the sponsor's bounds. In conducting this research we work within the following limitations:

- We limit the investigation to focus on enabling units, rather than primary warfighting units, as there has been very little work in the area of modeling force design of these types of units. Specifically, we limit ourselves to only the Air and Missile Defense (AMD) units and missions.
- Our scenario uses only Phase II: Seize the Initiative mission sets.

Assumptions are research-specific statements that are taken as true in the absence of facts. For this project, the team identified the following assumptions:

- Our use cases would serve as adequate proof of principle to demonstrate the power of our force design modeling methodology.

Methodology

Overview

Army force designs and force structures are currently developed as a part of the Army Force Management process. Concepts are developed, tested and implemented into doctrine within the various Centers of Excellence (COE) for each Army domain of warfighting. Force structure decisions are taken as a part of the Total Army Analysis process, which is underpinned by combat modeling and subject matter expert elicitation analysis. TRAC conducts analysis of different force designs and their effects on the larger Army, such as the Army End Strength Analysis study (Pippin, Pace, Schemm, Cunningham, & Castleberg, 2014), the BCT Design Options and Other Force Structure Trades study (Younger, et al., 2015), or the Force Design/ Force Mix: Building the Best Army Possible with Reduced End-Strength study (Dabkowski, Pippin, Twohig, Beck, & House, 2011).

We propose a method which develops force designs from fundamental constructs that are linked through tasks and capabilities to mission. Our methodology first defines a mission set associated with mission essential tasks quantified through mission attributes in a functional hierarchy. Our model matches units, defined at a fundamental level, using capabilities of the units quantified through the same mission attributes and tasks, to specific tasks that complete the given mission. These mission sets are defined at the operational level down to tactical, collective mission essential tasks. Figure 1 is a depiction of the core ideas of our force design model.

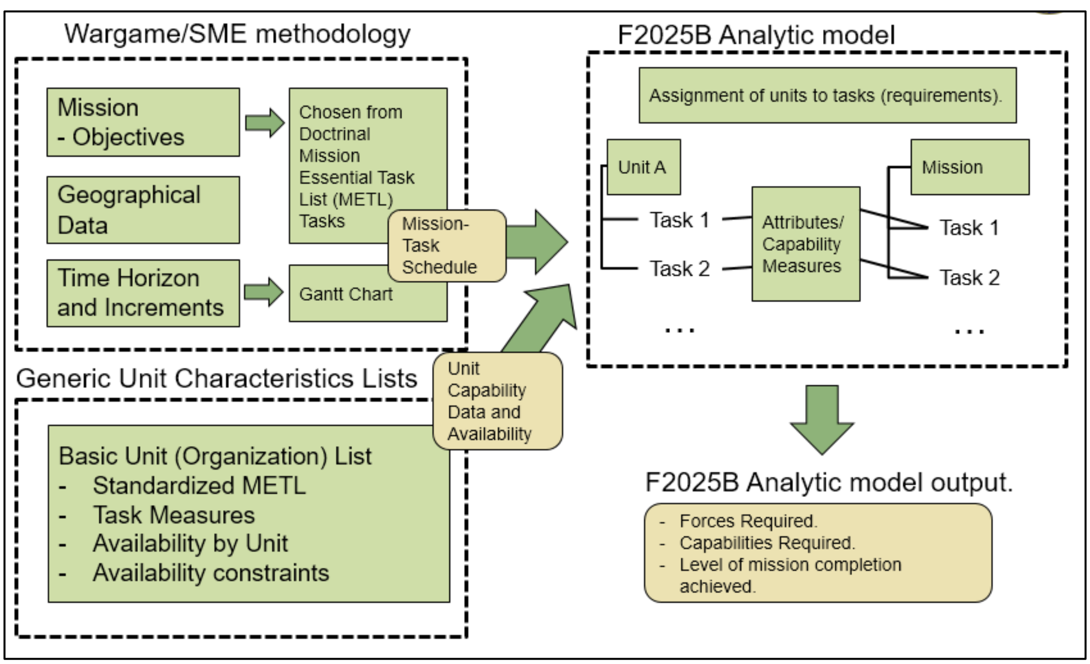

Figure 1: Description of Force Design Model

Figure 2 shows an overview of our methodology. In step 1, literature review, we conduct the standard literature review and scope the particular force design problem. From the literature review, some main outputs are potential data sources and constraints on force design solutions for our particular enabler unit and mission area.

Model Development and Data Model Design, together consist of four tasks. First, the Data Model is developed using the data sources identified in step 1. This includes developing the unit capability data, unit availability data, and scenario specification. We use a combination of SME elicitation techniques and online data sources such as FMSweb, (https://fmsweb.army.mil), and the Army Training Network (ATN) (https://atn.army.mil). There are many SME elicitation techniques available for constructing a functional hierarchy model, unit capability data, and scenario specification. See reports by Marks, Smead, & Alt, 2013, or Teter, 2014 for a discussion of some common SME elicitation techniques.

Scenario specification must consist of identifying the overall objective and mission, then specifying sub-missions that must be accomplished to complete that objective. To fully specify the scenario, we must create a map of those missions to mission essential tasks that can be conducted by specific types of units.

Scenario specification is best done through SME elicitations such as staff training exercises or Wargaming. Unit data can be found on FMSweb databases to give the total numbers of each type of unit within the force design unit and mission area we are investigating. Unit availability data can be taken from TPFDD data or other unit readiness data sources. Unit capability data and functional hierarchies, including task completion attributes should be developed using SME elicitation.

Next, we develop the model. The objective function is developed using a decision analysis technique formally referred to as multiple attribute decision theory (Raiffa & Keeney, 1976), also known by the name popularized by Keeney in 1972 (1994) as Value Focused Thinking (VFT). The functional hierarchies are constructed and then capability attributes for the associated units are assigned to lower tiers of the hierarchy. Each unit type is evaluated against the capability attributes to determine a quantity which we refer to as unit mission value. Putting it differently, the unit mission value is defined by the functional hierarchy and later used as the objective function coefficient for the decision variable corresponding to that unit type. A further discussion of what a functional hierarchy looks like and what we mean by objective coefficients is presented later in this document. The final task in the model development is running the model on our developed data set and extracting the analytic results.

Steps 3 and 4 in our process is to conduct an operational analysis using this unit mission area specific model and reporting the results.

In our research, we apply this methodology to one simplified example under an unclassified scenario derived from a TRAC Standard Scenario. One weakness of this research is that we only show how we developed the model for this case and not what types of force design operational analyses can be conducted using the model.

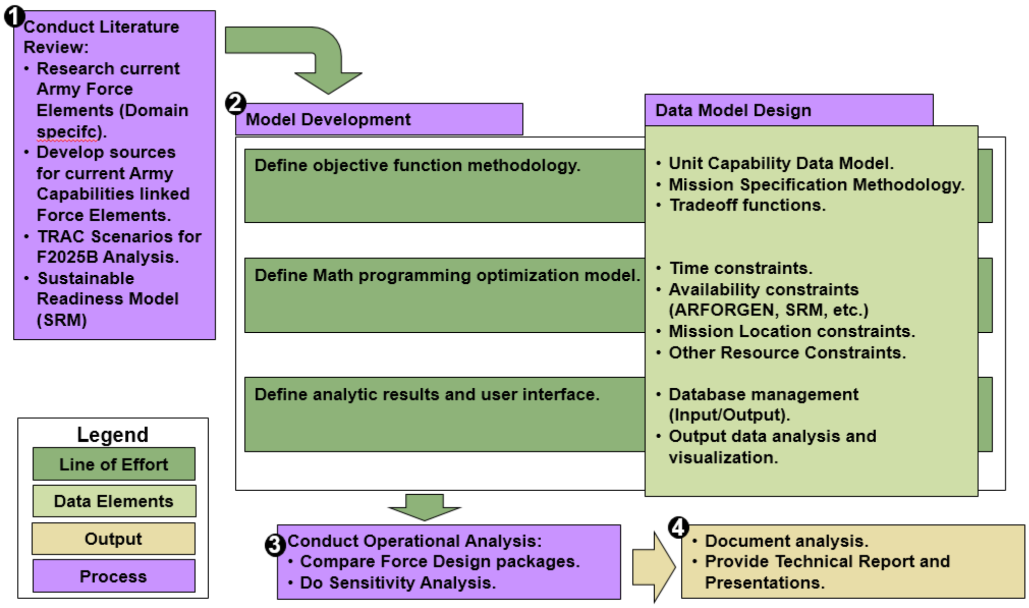

Figure 2: Project Methodology Overview

Objective Function Methodology and Data Model Design

There are essentially four phases in developing the data required for the Force Design model, the first two of which should execute concurrently. First, we develop capability and doctrinal tasks associated with particular Army units to be included in a force design analysis. Second, we develop a scenario, or set of scenarios, within which analyses of various force designs will take place. Third, we develop value models associated with each mission required in the analytic scenario(s). Finally, we develop capability data for each of Army unit in our analysis based on the attributes being measured in our defined value models.

Development of Unit doctrinal, standardized Mission Essential Task Lists (METLs)

Most of our example unit level data originates from FSMweb (https://fmsweb.army.mil), from which we extract unit types and named units of each type resident in the current total force. We use the Army Training Network (ATN) (https://atn.army.mil), which contains the Central Army Registry, to obtain all approved unit task lists by unit type.

It is important to note here that we make a distinction between unit types and units available. Each unit available has a unit type. Each unit type has characteristics that give it capabilities for completing different tasks, as described in our unit type task list, which is initially derived from the collective tasks lists for each unit type. The Army develops and updates these unit collective tasks lists regularly.

A SME reduces our unit type task lists to match our developed scenarios using professional military judgement. A SME ensures that tasks selected for the METL of each unit type are those important to the unit's core capabilities. Results of this phase are a set of METL's for each unit type. These METL's guide development of the mission required tasks in the scenario as well as guide development of the unit capabilities based on the attributes defined during the value modeling phase.

Scenario Development for Force Design Analysis

We conduct scenario development based on TRAC Standard scenarios. Scenario development begins with specifying the overall strategic mission, then listing required tasks in time and space within the specific force design unit and mission area being analyzed. These sub-tasks, we call them mission tasks, all contribute in some way toward the central objective of the scenario's strategic mission. For our model, we limit consideration of these mission tasks to only one mission area at a time, such as AMD, engineer, or logistics. This simplifies the problem and begins to prevent interdependencies between different capabilities from causing problems in our model.

There are several SME elicitation techniques that can be useful for providing the type of information needed to define the scenario fully. The simplest way to think about the problem of developing a scenario is as a problem of planning an operation. A focus group that walks SMEs from the mission area being analyzed through the planning process or data from a group of SMEs conducting a wargame around the central objectives of the base scenario should provide sufficient information to develop the scenario. The initial scenario development for our methodology requires only a task list and start and end times of each task. Table 1 shows the basic data needed for our example model in the AMD unit and mission space.

Table 1: Example of data required in the Mission Task List

Mission ID	Mission	Start Time	End Time
0	Unit Idle	0	13
1	Employ AMD at FOB One	1	12
2	Employ AMD at FOB One	1	12
3	Employ AMD at FOB Two	1	12
4	Employ AMD at FOB Two	1	12
5	Employ AMD at OBJ Rockfish	6	10
6	Employ AMD at OBJ Flounder	6	10
7	Employ AMD at OBJ Swordfish	2	8
8	Employ AMD at OBJ Squid	2	8
9	Employ AMD at OBJ Shark	6	12

Functional Hierarchy Development and Definition of Mission Value

Value models consist of basically two parts; an objective (or functional) hierarchy linking the overall objective through sub-objectives (or tasks) to attributes (or required capabilities); and a set of value functions that can (arbitrarily) provide measures for capability contribution to each attribute in the functional hierarchy (Raiffa & Keeney, 1976). Essentially the functional hierarchies are mappings of the set of tasks and supporting tasks required to complete a given mission task. Each mapping is constructed using SME professional military judgement input. For our force design model, a functional hierarchy must be mapped to the level of unit for which the analysis is taking place. For example, if we are conducting a platoon level analysis of force design, we must ensure that our tasks are "sized" for the platoon level. We would not, for instance, assign a platoon of infantry to attack an objective containing a division of enemy infantry.

At the base of each of these functional hierarchies exist attributes, or measures of capability. In our model, mission completion is measured using these attributes tied to value functions. The value functions output the value each unit brings to the mission based on their capability. Value functions are described in more detail in the next section. We borrow the bulk of our value model methodology from multi attribute decision theory (Raiffa & Keeney, 1976).

At the core, these value models coupled with the scenario missions and fed by the Unit capability data define the objective function of the F2025B Force Design model. The central idea is to maximize the value of a force design's contribution to mission completion. By way of definition, the "value" of a force design only has any meaning compared to other force designs developed within the same solution space. The objective function, then, can be thought of as the sum of the amount of value that each Unit brings in a particular time period for performing a particular task.

The value modeling approach is somewhat subjective and changes between different mission areas. The analyst should, in particular, conduct sensitivity analysis on the "size" of unit tasks.

An example objective hierarchy is:

Table 2: AMD Functional Hierarchy Input Data

Node Id	Node Name	Node Type	Node Parent Id	Node Parent Name	SubObj Level
1	Employ Air and Missile Defense (AMD)	High Level Task	NA	NA	1
2	Conduct AMD Engagements (Shoot)	Sub Objective	1	Employ Air and Missile Defense (AMD)	2
3	Conduct AMD Sensor Ops (Sense)	Sub Objective	1	Employ Air and Missile Defense (AMD)	2
4	Max. Altitude (Engage)	Attribute	2	Conduct AMD Engagements (Shoot)	3
5	Max Threat Speed	Attribute	2	Conduct AMD Engagements (Shoot)	3
6	Proportion of Area Covered (Shoot)	Attribute	2	Conduct AMD Engagements (Shoot)	3
7	Max. Altitude (Sense)	Attribute	3	Conduct AMD Sensor Ops (Sense)	3
8	Min. Altitude (Sense)	Attribute	3	Conduct AMD Sensor Ops (Sense)	3
9	Max Threat Speed	Attribute	3	Conduct AMD Sensor Ops (Sense)	3
10	Proportion of Area Covered (Sense)	Attribute	3	Conduct AMD Sensor Ops (Sense)	3

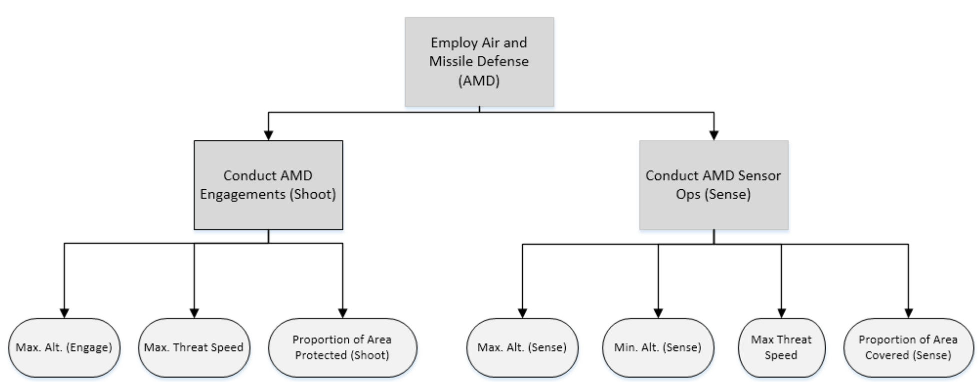

Figure 3: Diagram of the AMD Functional Hierarchy

Figure 3 depicts a functional hierarchy for our proof of principle mission set. These functional hierarchies are carefully developed by SME's in the unit and mission area being analyzed for each task.

There will be a different value model for each mission/task within the overall scenario strategic mission. Some may have similar value models if there are only small changes, for instance, over time or location. However, even in the cases of time and location, there may be differences in the value model used for a particular mission objective or mission task. These differences may be subtle, but should be considered. In our formulation, we assume constant value models over time and location. We use mission weighting in the objective function to show relative importance of a mission in one location over the same type of mission in a different location.

We attempt to keep all the sub-objectives and attributes additive. That is to say that they are mutually exclusive, independent, and are collectively exhaustive of the mission space. As this is a model, the collectively exhaustive stipulation can be somewhat relaxed, as we are most interested in analyzing those factors that are most important to the system under study, rather than all of them. If there is a significant correlation between sub-objectives, than an assumption of independence may not be appropriate. Though, most of the time, small correlations can be ignored as they are not impacting the mission significantly. Nonetheless, this is something that must be tested for with sensitivity analysis.

Value Functions

Each attribute has a value function specified with it. The function specifies the value that a certain level of capability gives for that particular attribute.

Our input data structure of our AMD example is shown in Table 3:

Table 3: AMD Attribute Value Functions Input Data

ID	Attribute	Min	Max	PlotType	Rho	Weight
1	Max Altitude Engage	0	50	Increasing Convex	5	0.142857143
2	Max Threat Speed	0	3600	Increasing Concave	2500	0.142857143
3	Perc Area Covered	0	1	Increasing Linear	inf	0.142857143
4	Max Alt Sense	0	50	Increasing Convex	5	0.142857143
5	Min Alt Sense	0	50	Decreasing Concave	3	0.142857143
6	Max Threat Speed Sense	0	3600	Increasing Concave	2500	0.142857143
7	Perc Area Covered Sense	0	1	Increasing Linear	inf	0.142857143

This set of value functions is for the value model specific to the "Employ AMD against low altitude, low speed threats" mission task. It is easy to programmatically construct different functions using a parameterization scheme. For our methodology, we use several different functions, including linear, step-wise, and exponential functions. Yet, there are many shapes that can be parameterized for programmatic access. In the data of Table 3, we use an exponential function to provide our value function shapes. The ρ (Rho) value column is a parameter that describes the degree of curve. For example, in Figure 4, the shape is increasing, left to right, and convex (Increasing Convex plot type). A smaller ρ would cause a steeper initial climb, where a $\rho = 0$ creates essentially a straight line (though in our function we actually do not use ρ for linear functions).

As is shown in Table 3, each value function is weighted. The total value provided for the functional hierarchy shown in Table 3 is simply the weighted sum across the value functions. This total value for one mission task represented by a functional hierarchy such as the one in Table 3 can then be inserted into the objective function as a coefficient for a decision variable for a single unit type evaluated by these value functions.

For example, the function for the low altitude threat "Max Altitude of Threat (Engage)" value function is shown in Figure 4. The value of a particular unit is calculated by inputting the maximum altitude at which that unit can engage a threat and outputting the value of using that unit to accomplish the task of engaging low altitude threats.

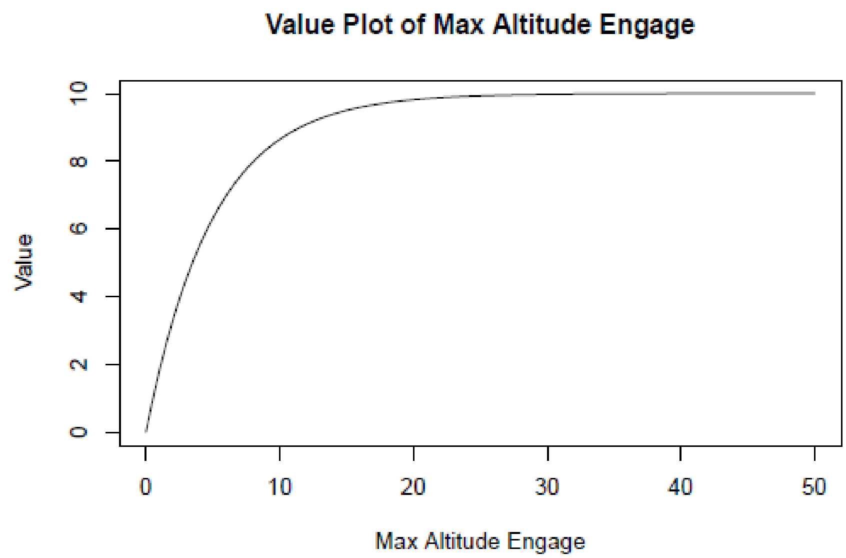

Figure 4: The value function plot for the "Max Altitude of Threat (Engage)" attribute. As the range capability of the unit increases, it provides more value to task completion.

Once each value for a particular unit type is calculated, they are summed, with the pre-determined weights. Now the coefficient for the decision variable in the objective function for whether a particular unit of that particular type performs this mission task is equal to the value output by this value model.

A wholly different value function may be required for a different task. For the ADA example, engaging low altitude threats and engaging high altitudes threats may be two different tasks. A unit that can only engage low altitude threats is preferable when engaging low altitude threats, and therefore should obtain a higher value on the value function, than a unit that can only engage high altitude threats when engaging low altitude threats. And vice versa. Additionally, a unit that can engage throughout the range of threats may obtain the most value. Therefore, there needs to be a different value function for each of the tasks, engage low altitude threats versus engage high altitude threats.

Keep in mind that in our example we define attributes such as "low altitude" or "high altitude", etc., in a quantitative sense to ensure specificity. In out example, we define low altitude as between 0 and 5 kilometers above sea level, medium altitude as between 5 and 12 kilometers, and high altitude as between 12 and 50 kilometers. This partitioning of a variable should come from unit and mission area knowledge and is meant to help make planning a scenario more intuitive. If this variable were used as a continuous variable, then there can be infinite number of tasks involving altitude of threat, for instance, and therefore infinite number of value models, which we wish to avoid. Our interactive R Shiny application (shown in Figure 5) allows users to change value functions, using .csv file input of the same data as in Table 3. A copy of the code is available upon request. (PLACE A LINK TO R SHINY APP ON SERVER)

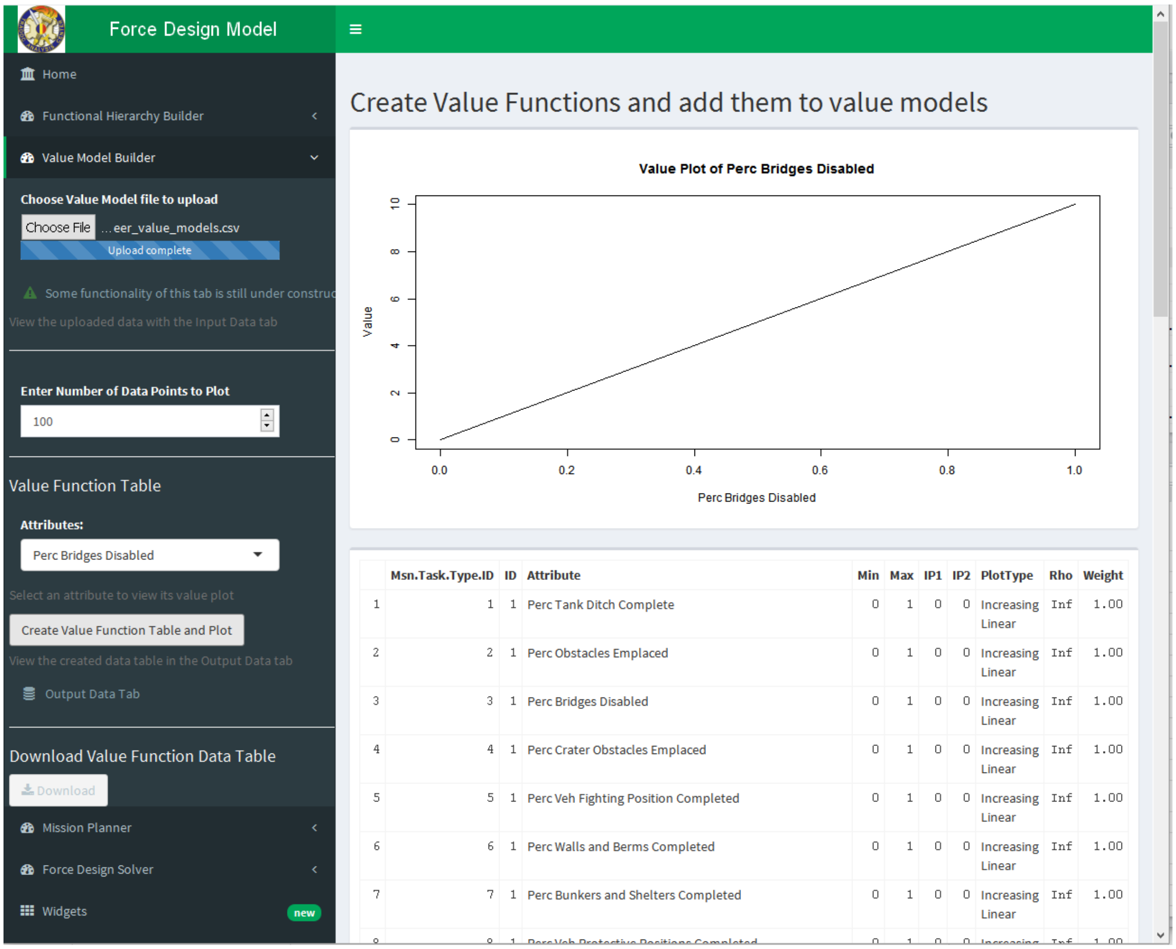

Figure 5: R Shiny App for processing value function data.

Unit Capability Data Development

Just like in the Unit METL phase, we start by deciding which units to leave in the model and which to leave out. Then, we look at all the value models (which by this point should be synonymous with mission task break down to measurement attribute) and find all the unique attributes that require some data describing a units capability to complete that task. For example, if the attribute is the maximum altitude of threat during engagement, than a necessary quantity to show for each unit type is the maximum altitude of threat that the particular unit can engage.

Input data structure for unit type capabilities for our AMD example is shown in Table 4:

Table 4: Capabilities for each ADA unit type within each attribute category.

Unit Type	Unit Type Sub-Unit ID Num	Max. Altitude (Engage)	Max Threat Speed	Coverage Area (Shoot)	Max. Altitude (Sense)	Min. Altitude (Sense)	Max Threat Speed	Coverage Area (Sense)
ADA Battery (AVENGER) IFPC Bn	1	12	900	10	12	0	2300	10
ADA Battery (AVENGER) Comp Bn	2	12	900	10	12	0	2300	10
ADA Battery (AVENGER)	3	12	900	10	12	0	2300	10
ADA Battery (AVENGER) ABN	4	12	900	5	12	0	2300	5
ADA Battery (Intercept)	5	5	2300	2	5	0	2300	2
ADA Battery (JLENS) (SEPARATE)	6	0	0	0	25	0	2300	100
ADA Battery (PATRIOT) 1	7	12	2300	25	12	0	2300	25
ADA Battery (PATRIOT) 2	8	12	2300	25	12	0	2300	25
ADA Battery (THAAD) (SEPARATE)	9	50	3600	100	50	12	3600	100

Unit capabilities can be developed from many open sources, but if necessary, can also be developed from classified numbers. For this type of analysis, we must certainly balance the need for accuracy in the numbers with the need to keep the analysis accessible and flexible.

Next we develop a list of all available units. This list should include the unit type and its available start and end time periods. The unit availability list should look like the data in Table 6 in Appendix B. At a minimum, the data must have a unit name, unit type, a unit type identification number, and start and end times for availability.

Calculating the Value of Mission Task Completion

This step consists of inputting all the data developed so far, including value models and unit type lists, and calculating the value of each unit type performing each mission. To do this, we must further specify each of the missions or tasks in the scenario mission list so that the model understands which value model to use in calculating the unit type value added by performance of this mission.

Fully Specifying the Mission Task List

We take the scenario mission task list and specify the type of tasks. Care must be taken to ensure that the tasks in the mission list are sized generally correctly for the unit types under consideration. In some cases additional tasks may need to be added or subtracted as the task is more fully specified. For example, in the ADA example, we may have a requirement to provide air and missile defense at FOB One. There will be both low altitude threats and high altitude threats. However, there may be enough threats of each type to warrant specifying a low altitude task and a high altitude task so that the model will assign two different units. The same could be said if there are only low altitude threats, but the scenario designer knows that there are more than enough threats to keep at least two of the general size units, in this case battery or company level, busy, or there may be a huge area to cover and more than one battery sized unit (of any type) is known to not be capable of covering the whole area. Then we should specify two or more low altitude engagement tasks.

Requirements are then added to the tasks that correspond to the attributes of the specific value models for that tasks. If a value model, with appropriate value functions, was not created for that specific task, then a value model to match that specific task must be created. Any additional attributes then must be considered and unit type capabilities updated to include unit capabilities for the new attributes. In this way, the data development process can be iterative as the analyst refines the model. Table 7 in Appendix B is an example of input data for a fully specified scenario mission task. The necessary data for mission task specification includes mission name, start and end time periods, and a measure of “how much” of the mission is required along the attributes in the value model for that mission task. For the AMD example, each mission task is defined in six attributes. Note that the altitudes and speeds for the AMD example are specified in three different ranges. The number in the table corresponds to the range required to complete the given mission task.

Calculating Values of Units Performing each Mission

Next, for each mission, we calculate a value, using the value model for that mission, for each unit type. Sometimes there is an additional function that maps the unit capability to the attribute. This function should take as input the required capability specified by the mission or task definition and the capability of the unit. For instance, the attribute "Proportion of Area Covered" entails the total area that the unit is capable of covering divided by the required capability to perform the task. This number is then used to determine the value that the unit contributes to completion of that task.

Table 8 Appendix B shows output in a matrix of unit type to mission value (R code for calculating this matrix is available upon request), where unit types are along the rows and mission tasks are along the columns. The numbers in Table 8 essentially become the coefficients in the objective function of our MIP optimization formulation.

Mixed Integer Program Formulation

The primary model can be stated as a mixed-integer linear programming model. Notation and formulation is presented here in the Naval Postgraduate School (NPS) formal style (Brown & Dell, 2007):

Indicies

m, m'	missions (also referred to as tasks) and the associated alias.
u	units
t	time segments (also referred to as periods).

Derived Sets

$UMT_{u,m,t}$	derived set of all units *u* that may be assigned mission *m* in period *t*.
$MT_{m,t}$	derived set of all missions *m* that should be accomplished in period *t*.

Parameters [units]:

$umvalue_{u,m,t}$	value received if unit u is assigned to mission m in period t. The “unit mission value” is a derived parameter determined by the functional hierarchy model.

pen	small data specific penalty that ensures units are not assigned unnecessarily.

Decision Variables [units]:

Z	objective function value. [unit mission value]
$X_{u,m,t}$	binary variable with value 1 if unit *u* is assigned to mission *m* in period *t.*
$Y_{u,m,t}$	binary variable with value 1 if unit *u* is not assigned to mission *m* in period *t* after being assigned to mission *m* the previous period *t-1*.

Objective:

$$\text{Maximize} \sum_{u,m,t|UMT_{u,m,t}} umvalue_{u,m,t} X_{u,m,t} - \sum_{u,m,t|UMT_{u,m,t}} pen Y_{u,m,t} \quad (1)$$

Constraints:

$$\sum_{u|UMT_{u,m,t}} X_{u,m,t} = 1 \quad \forall m,t \,|\, MT_{m,t} \quad (2)$$

$$\sum_{m|UMT_{u,m,t}} X_{u,m,t} \le 1 \quad \forall u,t \quad (3)$$

$$\sum_{m'|\mathrm{m}\ne\mathrm{m}'\cap UMT_{u,m,t}} X_{u,m,t-1} + X_{u,m,t} \le 1 \quad \forall u,m,t|UMT_{u,m,t} \quad (4)$$

$$X_{u,m,t-1} + X_{u,m,t} \le Y_{u,m,t} \quad \forall u,m,t|UMT_{u,m,t} \quad (5)$$

$$X_{u,m,t} \in \{0,1\} \quad \forall u,m,t \quad (6)$$

$$Y_{u,m,t} \in \{0,1\} \quad \forall u,m,t \quad (7)$$

Formulation Discussion

The objective function, Equation (1), selects those unit and mission pairings that maximizes the total value over all time periods while at the same time minimizes the unit moves between missions. Equation (2) ensures that one and only one unit will be assigned to all missions in each time period. Equation (3) ensures that a unit will not be tasked to more than one mission during each time period. Equation (4) requires that a unit cannot move from one mission to another in a subsequent time period immediately following the last. Equation (5), in conjunction with

Equation (4), ensures that a unit which is reassigned to another mission in a subsequent period incurs a “unit movement and setup” penalty. Equations (6) and (7) enforce the binary constraints.

This formulation is customized for a specific data set defined in the later sections of this paper. As such this formulation serves as a frame work for other scenarios. For example, Equation (4) implies that one period is required between mission moves. In cases where more than one period is required to move from one mission to another, the only change that is required to Equation (4) is the appropriate change to the right hand side of equation (4). As demonstrated, precedence is demonstrated in constraints (4) and (5) and can easily be scaled to other scenarios by either using the same constructs or adding additional constraints as necessary.

Bringing it Together: Solving the model

Finally, we manipulate the data into an objective coefficient vector and constraint matrices using a series of scripts. We have implemented several R scripts that automate this and produce the necessary files. Once we have the data calculated in the correct format, we use solving software to solve for the optimal force design. Table 5 shows the raw output of solving using GAMS with the CPLEX solver combined with the unit name and type of each unit the model chose within each time period. Our methodology can be used with any popular algebraic modeling and solver software, including packages such as pyomo in Python or lpSolve in R using the lp_solve solver software. We have currently implemented it in GAMS/CPLEX.

Table 5: AMD Example GAMS Solver output.

****

T1

Mission	Unit	Value	Unit Name	Unit Type	Unit Type	Avail (T >=)	Not Avail (T>=)
M1	U7	10	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M2	U53	9	D BATT, 4TH BATTALION, 3D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M3	U63	10	D BATT, 3D BATTALION, 4TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	1	28
M4	U2	9	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27

T2

Mission	Unit	Value	Unit Name	Unit Type	Unit Type	Avail (T >=)	Not Avail (T>=)
M1	U7	10	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M2	U53	9	D BATT, 4TH BATTALION, 3D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M3	U63	10	D BATT, 3D BATTALION, 4TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	1	28
M4	U2	9	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M7	U24	9	D BATT, 2D BATTALION, 43D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M8	U1	9	A CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	2	29

T3

Mission	Unit	Value	Unit Name	Unit Type	Unit Type	Avail (T >=)	Not Avail (T>=)
M1	U7	10	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M2	U53	9	D BATT, 4TH BATTALION, 3D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M3	U63	10	D BATT, 3D BATTALION, 4TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	1	28
M4	U2	9	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M7	U24	9	D BATT, 2D BATTALION, 43D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M8	U1	9	A CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	2	29

• • •

T10

Mission	Unit	Value	Unit Name	Unit Type	Unit Type	Avail (T >=)	Not Avail (T>=)
M1	U7	10	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M2	U53	9	D BATT, 4TH BATTALION, 3D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M3	U63	10	D BATT, 3D BATTALION, 4TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	1	28
M4	U2	9	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M5	U55	9	BATTERY B, 2D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (THAAD) (SEI	9	5	32
M6	U54	9	BATTERY A, 2D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (THAAD) (SEI	9	1	28
M9	U29	9	BATTERY D, 2D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (THAAD) (SEI	9	4	31

T11

Mission	Unit	Value	Unit Name	Unit Type	Unit Type	Avail (T >=)	Not Avail (T>=)
M1	U7	10	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M2	U53	9	D BATT, 4TH BATTALION, 3D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M3	U63	10	D BATT, 3D BATTALION, 4TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	1	28
M4	U2	9	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M9	U29	9	BATTERY D, 2D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (THAAD) (SEI	9	4	31

T12

Mission	Unit	Value	Unit Name	Unit Type	Unit Type	Avail (T >=)	Not Avail (T>=)
M1	U7	10	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M2	U53	9	D BATT, 4TH BATTALION, 3D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	28
M3	U63	10	D BATT, 3D BATTALION, 4TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	1	28
M4	U2	9	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	27
M9	U29	9	BATTERY D, 2D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (THAAD) (SEI	9	4	31

This information can be useful to planners when arranging forces against missions over time. It can also be analyzed to gain insights about the types of units that are most cost effective, giving a reasonable amount of mission success, against different mission types. Also, this data can give us insights about the right mix of units at every echelon that provides flexibility and robustness to changes in mission.

Summary

The methodology we present here provides a way to think about how to design our Army forces to meet mission demands in terms of tasks that are required for mission completion. We show how a set of data can be constructed to map a unit's capabilities to required tasks using doctrinal tasks and missions.

Our research represents the initial work in using this type of methodology to construct force design models using a mission-focused, task-based, capability architecture. We demonstrate our force design methodology and possible insights that come from the methodology. However, due to time and resource constraints, we have not finished developing a full trade-space visualization tool. Additionally, many improvements can be made with future research, building on this base methodology to develop tools for increasing the effectiveness of this methodology, such as a web-based tool to quickly create and save force capability data and value models.

One major result of our research is the discovery that each enabler unit mission set requires a construction of a set of unique value models, though using the same MIP formulation. Our research also concluded that initial development of the functional hierarchies and value functions is difficult and time consuming. Future research can explore different methods for overcoming these limitations, such as developing libraries of these models for each unit mission area. These libraries can be made readily available and can be updated periodically as tasks and missions change over time, which is much easier than initial development.

Further work is needed, but this methodology provides good insights and may well prove to have much more accessible results at shorter timelines than many existing analytic alternatives. Our methodology provides a clear, objective way to use concrete data in conjunction with well-reasoned subjective inputs to provide insights into U.S. Army force design.

Appendix A - References

Brown, G. G., & Dell, R. F. (2007, January). Formulating Integer Linear Programs: A Rogues' Gallery. *INFORMS Transactions on Education*, *7*(2), 1-13.

Dabkowski, M., Pippin, B., Twohig, J., Beck, C., & House, J. (2011). *Force Design/Force Mix: Building the Best Army Possible with Reduced End-Strength.* Fort Leavenworth: TRADOC Analysis Center.

Keeney, R. L. (1994). *Value-Focused Thinking: A Path to Creative Decision Making.* Cambridge: Harvard University Press.

Marks, C., Smead, K., & Alt, J. (2013). *Enhancing Subject Matter Expert Elicitation Techniques.* Monterey: TRADOC Analysis Center - Monterey.

Pippin, B., Pace, R., Schemm, R., Cunningham, S., & Castleberg, W. (2014). *Army End Strength Analysis.* Fort Leavenworth: TRADOC Analysis Center.

Raiffa, H., & Keeney, R. L. (1976). *Decisions with Multiple Objectives: Preferences and Value Tradeoffs.* New York: Wiley & Sons.

Teter, M. (2014). *Applying Subject Matter Expert (SME) Elicitation Techniques to TRAC Studies.* Monterey: TRADOC Analysis Center - Monterey.

Younger, G., Black, S., Stitt, G., Swain, A., Pruitt, J., & Leath, L. (2015). *BCT Design Options and Other Force Structure Trades.* Fort Leavenworth: TRADOC Analysis Center.

Appendix B – Tabular Data for AMD Proof of Principle

Table 6: Notional unit availability data for ADA units.

Unit Id	UIC	Unit Name	Unit Type	Unit Type ID	Avail (T >=)	Not Avail (T>=)
1	WA1AAA - 1	A CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	2	2
2	WA1AAA - 2	B CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	0
3	WA1AAA - 3	C CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	1	1
4	WA1AAA - 4	D CO, 4th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	0
5	WAC2AA-1	A CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	0
6	WAC2AA-2	B CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	0
7	WAC2AA-3	C CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	0
8	WAC2AA-4	D CO, 1st BATTALION, 1ST AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 2	8	0	0
9	WAW0AA-1	A CO, 6th BATTALION, 52D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	5	5
10	WAW0AA-2	B CO, 6th BATTALION, 52D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	0	0
11	WAW0AA-3	C CO, 6th BATTALION, 52D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	0	0
12	WAW0AA-4	D CO, 6th BATTALION, 52D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (PATRIOT) 1	7	2	2
13	WAW0AA-5	E CO, 6th BATTALION, 52D AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER) Comp Bn	2	5	5
14	WAWLAA-1	A BATT, 5th BATTALION, 5TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER) IFPC Bn	1	9	9
...	...	...	...	...	...	...
91	WYJZAA-3	C BATT, 1ST BATTALION, 188TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	5	5
92	WYKSAA-1	A BATT, 3D BATTALION, 265TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	5	5
93	WYKSAA-2	B BATT, 3D BATTALION, 265TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	5	5
94	WYKSAA-3	C BATT, 3D BATTALION, 265TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	5	5
95	WYKVAA-1	A BATT, 1ST BATTALION, 265TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	5	5
96	WYKVAA-2	B BATT, 1ST BATTALION, 265TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	10	10
97	WYKVAA-3	C BATT, 1ST BATTALION, 265TH AIR DEFENSE ARTILLERY REGIMENT	ADA Battery (AVENGER)	3	2	7

Table 7: Fully specified mission list including required capabilities in order to successfully complete each mission task.

Mission ID	Mission	Start Time	End Time	Max. Threat Altitude for Engagement	Max. Threat Speed	Engagement Coverage Area	Threat Altitude for Sensing	Max. Threat Speed for Sensing	Sensor Coverage Area
1	Employ AMD at FOB One	1	12	1	1	25	1	1	25
2	Employ AMD at FOB One	1	12	2	2	25	2	2	25
3	Employ AMD at FOB Two	1	12	1	1	25	1	1	25
4	Employ AMD at FOB Two	1	12	2	2	25	2	2	25
5	Employ AMD at OBJ Rockfish	6	10	1	2	30	1	2	30
6	Employ AMD at OBJ Flounder	6	10	1	2	30	1	2	30
7	Employ AMD at OBJ Swordfish	2	8	1	2	15	1	2	15
8	Employ AMD at OBJ Squid	2	8	1	2	15	1	2	15
9	Employ AMD at OBJ Shark	6	12	1	2	30	1	2	30

Table 8: Value of each unit type conducting each of the 9 example AMD mission tasks.

Unit Type	Employ AMD at FOB One	Employ AMD at FOB One	Employ AMD at FOB Two	Employ AMD at FOB Two	Employ AMD at OBJ Rockfish	Employ AMD at OBJ Flounder	Employ AMD at OBJ Swordfish	Employ AMD at OBJ Squid	Employ AMD at OBJ Shark
ADA Battery (AVENGER) IFPC Bn	8.29	6.32	8.29	6.32	6.12	6.12	7.08	7.08	6.12
ADA Battery (AVENGER) Comp Bn	8.29	6.32	8.29	6.32	6.12	6.12	7.08	7.08	6.12
ADA Battery (AVENGER)	8.29	6.32	8.29	6.32	6.12	6.12	7.08	7.08	6.12
ADA Battery (AVENGER) ABN	7.71	5.74	7.71	5.74	5.65	5.65	6.12	6.12	5.65
ADA Battery (Intercept)	7.37	3.23	7.37	3.23	6.05	6.05	6.24	6.24	6.05
ADA Battery (JLENS) (SEPARATE)	5.71	5.07	5.71	5.07	5.07	5.07	5.07	5.07	5.07
ADA Battery (PATRIOT) 1	10.00	8.72	10.00	8.72	8.24	8.24	8.72	8.72	8.24
ADA Battery (PATRIOT) 2	10.00	8.72	10.00	8.72	8.24	8.24	8.72	8.72	8.24
ADA Battery (THAAD) (SEPARATE)	8.57	8.57	8.57	8.57	8.57	8.57	8.57	8.57	8.57

Appendix C - Acronyms

AMD	Air and Missile Defense
ADA	Air Defense Artillery
ATN	Army Training Network
BCT	Brigade Combat Team
CPLEX	Simplex Method Implemented in C
COE	Center of Excellence
F2025B	Force 2025 and Beyond
GAMS	General Algebraic Modeling System
MDMP	Military Decision Making Process
METL	Mission Essential Task List
MIP	Mixed Integer Program
NPS	Naval Postgraduate School
SME	Subject Matter Expert
TDA	Table of Distribution and Allowance
TPFDD	Time Phased Force Deployment Data
TOE	Table of Organization and Equipment
TRAC	TRADOC Analysis Center
TRADOC	Training and Doctrine Command
TRAC-MTRY	TRADOC Analysis Center- Monterey
VBA	Visual Basic for Applications